DM@Collider summary plots for Snowmass

Plans for DM simplified models

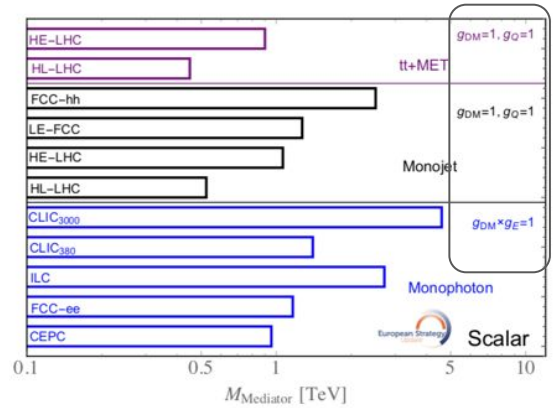
Boyu Gao (OSU)
Antonio Boveia (OSU)
Eric Corrigan (Lund University)

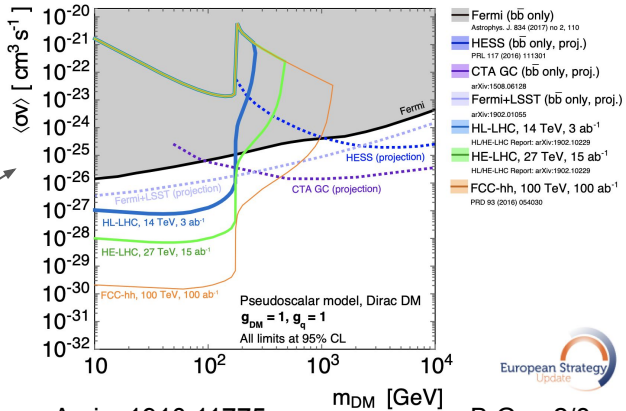
Our goal for DM@Collider plots for Snowmass

- Prepare Dark Matter summary plots like European strategy for HL-LHC and future colliders, for <u>DM simplified models with varying couplings</u>
  - Models used so far: from LHC Dark Matter Working Group [arxiv 1507.00966]
    - Vector/axial vector simplified model
    - Scalar/pseudoscalar simplified model

- Connect these plots to other experiments and Frontiers
  - Rare/precision Frontier: accelerator-based / fixed target experiments
  - Cosmic Frontier: direct detection and indirect detection
  - Will need to agree on benchmarks models and presentation of results with them

European Strategy: fixed couplings

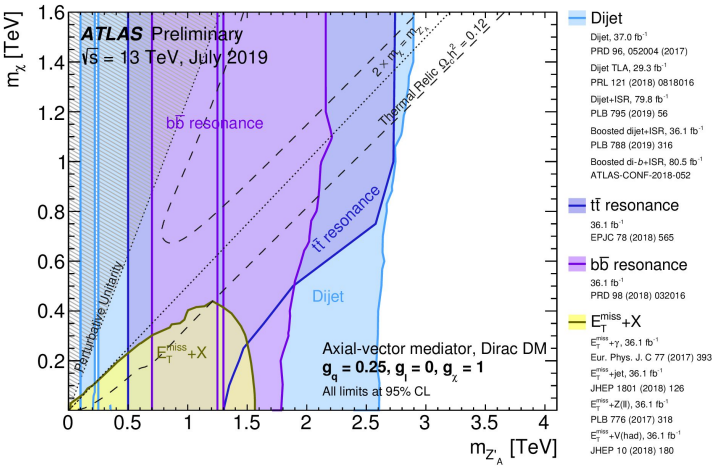


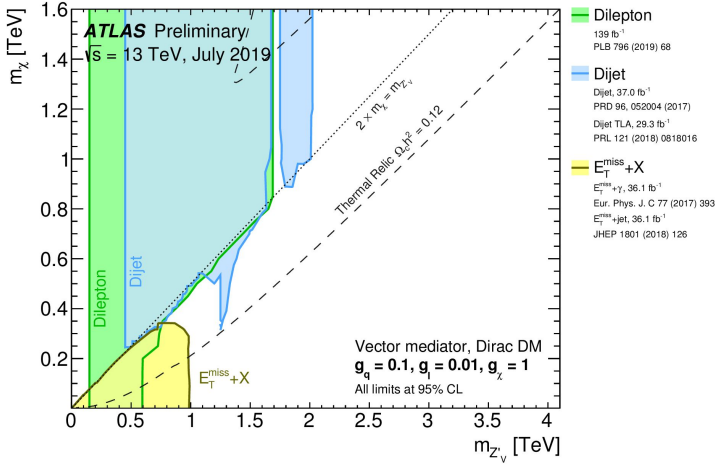


Arxiv: 1910.11775

Proposed summary plot #1: DM mass/mediator mass

- Vector/axial vector simplified models
  - Exclusions (shaded area) on Dark Matter mass - mediator mass plane with various couplings:
    - Vector simplified model (right figure)
    - Axial-vector simplified model (bottom figure)

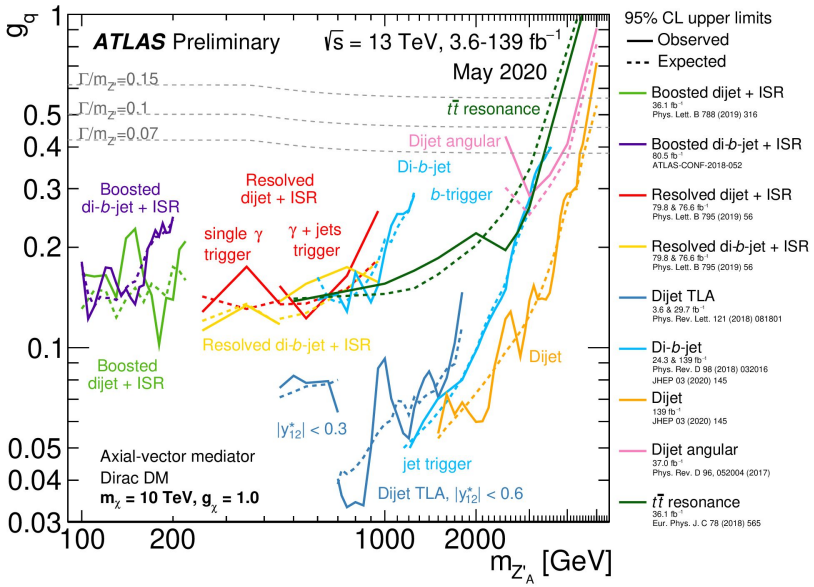




https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

Proposed summary plot #2: coupling vs mediator mass

- Vector/axial vector simplified models
  - Axial-vector simplified model (bottom figure): upper limits on mediator-quark coupling



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

Proposed summary plot #3: colliders and direct detection

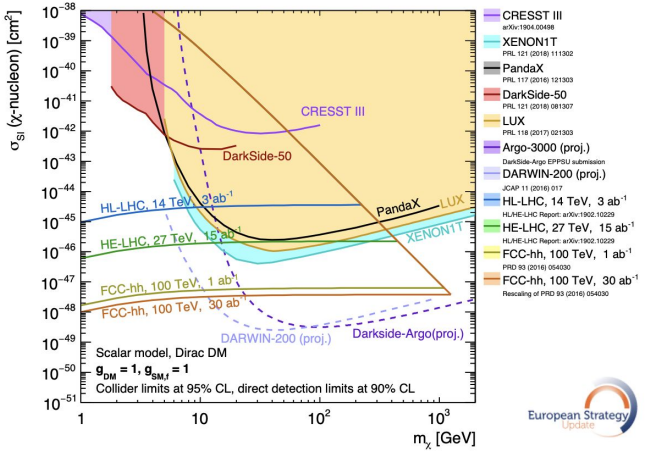
- Vector/axial vector simplified models
  - For axial vector mediator, the interaction is spin dependent: formula from arxiv 1603.04156

$$\sigma^{\mathrm{SD}} \simeq 2.4 \times 10^{-42}\ \mathrm{cm}^2 \cdot \left(\frac{g_q\, g_{\mathrm{DM}}}{0.25}\right)^2 \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\mathrm{GeV}}\right)^2 \quad [1]$$

- Scalar/pseudoscalar simplified models
  - For scalar mediator, the interaction is spin independent:

$$\sigma_{\mathrm{SI}} \simeq 6.9 \times 10^{-43}\ \mathrm{cm}^2 \cdot \left(\frac{g_q\, g_{\mathrm{DM}}}{1}\right)^2 \left(\frac{125\,\mathrm{GeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\mathrm{GeV}}\right)^2 \quad [2]$$

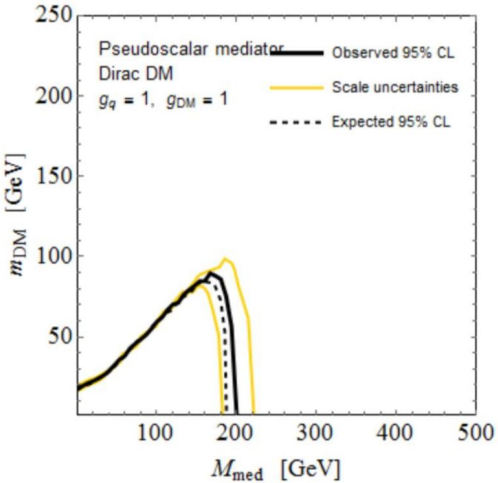
  - Translated results for future colliders are shown on the right



Arxiv: 1910.11775

Proposed summary plot #4: colliders and indirect detection

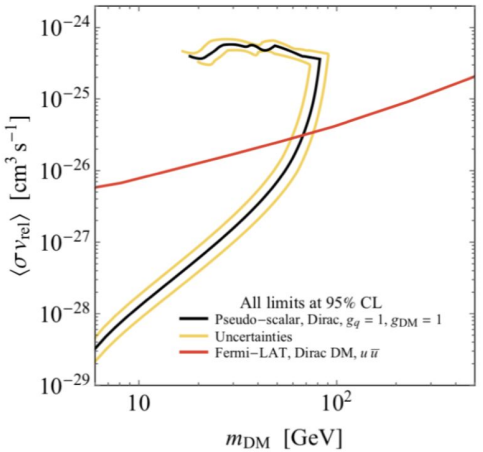
- Scalar/pseudoscalar simplified models
  - Fermi-LAT results are for Majorana DM: multiply Fermi bound by a factor of 2
  - Below is an limit translation example for pseudoscalar mediator



$$\langle \sigma v_{\rm rel} \rangle_q = \frac{3 m_q^2}{2\pi v^2} \frac{g_q^2 g_{\rm DM}^2 m_{\rm DM}^2}{(M_{\rm med}^2 - 4m_{\rm DM}^2)^2 + M_{\rm med}^2 \Gamma_{\rm med}^2} \sqrt{1 - \frac{m_q^2}{m_{\rm DM}^2}}$$

$$\Gamma^{\chi\bar{\chi}}_{\text{pseudo-scalar}} = \frac{g_{\rm DM}^2 M_{\rm med}}{8\pi} \left(1 - 4z_{\rm DM}^2\right)^{1/2},$$

$$\Gamma^{q\bar{q}}_{\text{pseudo-scalar}} = \frac{3 g_q^2 y_q^2 M_{\rm med}}{16\pi} \left(1 - 4z_q^2\right)^{1/2},$$



Arxiv: 1603.04156

List of analyses and collider options

- The list of analyses we can put on these plots
  - Jet+MET
  - Photon+MET
  - ttbar + MET (in contact with others in EF10 for these interpretations)
  - Di-jet / di-lepton
- The list of colliders
  - HL-LHC
  - Future colliders (including muon collider)
    - options discussed jointly between Energy and Accelerator Frontier meeting

Work plan

- These plots need individual inputs
  - We can start from DM simplified model results at a given coupling and mass
  - With an analytical interpretation (already done in CMS for visible results) we can make plots for other couplings as well → can discuss this in detail in another meeting
- After we agree on models, we could talk to future colliders / HL-LHC and collect the inputs from these searches
  - Preliminary work: agree on benchmark models, and validate Madgraph UFO and settings
    - Ongoing discussion with John Stupak III from MC task force
  - Some results already there from European Strategy, start with those
- Connect to other frontier and make summary plots
- We would like to write a LOI / whitepaper for Snowmass with those plots
  - Happy to work with others that want to make similar plots

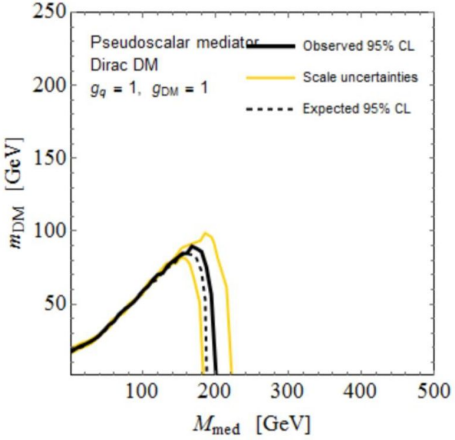
Thank you!

Backup slides

Arxiv: 1603.04156

Transferring collider limit to ID plane

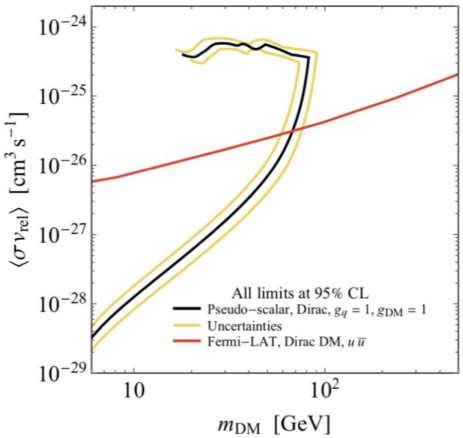
- Only translate the boundary lines from the LHC plot (left) to the mass-xsec plane (right)
- Since Fermi-LAT results are for Majorana DM, multiply Fermi bound by a factor of 2



$$\langle \sigma v_{\rm rel} \rangle_q = \frac{3 m_q^2}{2\pi v^2} \frac{g_q^2 g_{\rm DM}^2 m_{\rm DM}^2}{(M_{\rm med}^2 - 4 m_{\rm DM}^2)^2 + M_{\rm med}^2 \Gamma_{\rm med}^2} \sqrt{1 - \frac{m_q^2}{m_{\rm DM}^2}}$$

$$\Gamma^{\chi\bar{\chi}}_{\text{pseudo-scalar}} = \frac{g_{\rm DM}^2 M_{\rm med}}{8\pi} \left(1 - 4 z_{\rm DM}^2\right)^{1/2} ,$$

$$\Gamma^{q\bar{q}}_{\text{pseudo-scalar}} = \frac{3 g_q^2 y_q^2 M_{\rm med}}{16\pi} \left(1 - 4 z_q^2\right)^{1/2} ,$$



Arxiv: 1603.04156

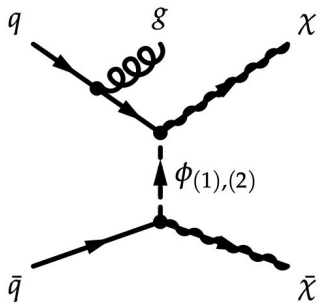
Transferring collider limit to DD plane - SI case

- DM interacting with nucleon via t-channel with simp scalar / vector mediator (SI case) has xsec of the form: $\sigma_{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}$, where mu is reduce mass
- For scalar mediator
  - DM-nucleon coupling reads (the difference between proton and neutron can be ignored in this case):

$$f^{n,p}(g_q) = \frac{m_n}{v}\left[\sum_{q=u,d,s} f_q^{n,p} g_q + \frac{2}{27} f_{\rm TG}^{n,p} \sum_{Q=c,b,t} g_Q\right]$$

    - Finally this simplifies to: $f(g_q) = 1.16 \cdot 10^{-3}\, g_q$
  - Hence the size of typical xsec reads:

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-43}\ {\rm cm}^2 \cdot \left(\frac{g_q\, g_{\rm DM}}{1}\right)^2 \left(\frac{125\,{\rm GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2$$



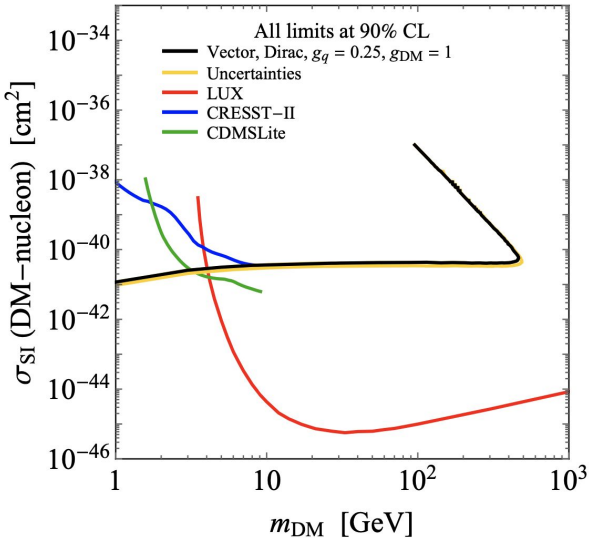
Arxiv: 1603.04156

Transferring collider limit to DD plane - SI case

- For the vector mediator
  - DM-nucleon coupling reads $f(g_q) = 3g_q$
  - Hence the size of typical xsec reads:

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_q\, g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2$$

- Compare DD results with translated LHC result (right figure):
  - Here they convert LHC limit for Vector mediactor (dirac DM) from 95% CL to 90% CL and compare the translated LHC result (using the above formula) to several most constraining experiments (see slide 3)



Transferring the limit - SD case

- For the axial-vector mediator, the scattering is SD
  - The corresponding xsec can be written as:

$$\sigma_{\mathrm{SD}} = \frac{3 f^2(g_q) g_{\mathrm{DM}}^2 \mu_{n\chi}^2}{\pi M_{\mathrm{med}}^4}$$

  - DM-nucleon coupling for protons and neutrons is given by:

$$f^{p,n}(g_q) = \Delta_u^{(p,n)} g_u + \Delta_d^{(p,n)} g_d + \Delta_s^{(p,n)} g_s$$

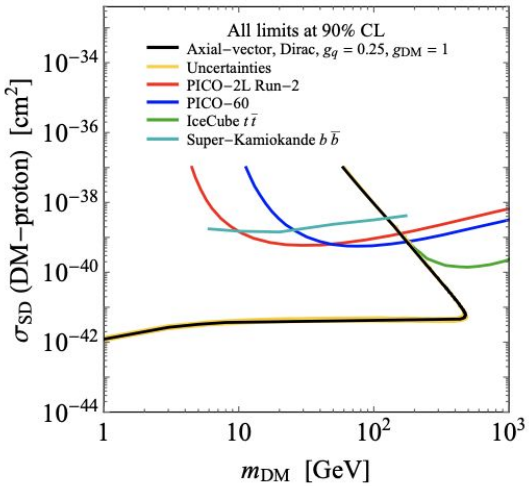
    - This can be simplified to $f(g_q) = 0.32 g_q$
    - The same result is obtained both for DM-proton scattering and DM-neutron scattering
    - Recommend to translate LHC limit to DM-proton xsec limit since this is harder to constrain by DD experiments

Transferring the limit - SD case

- Hene for the axial-vector mediator, the size for typical xsec reads:

$$\sigma^{\mathrm{SD}} \simeq 2.4 \times 10^{-42}\ \mathrm{cm}^2 \cdot \left(\frac{g_q\, g_{\mathrm{DM}}}{0.25}\right)^2 \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\mathrm{GeV}}\right)^2$$

- Compare DD results with translated LHC result (right figure):
  - The IceCube t-tbar and Super-Kamiokande b-bbar are results from neutrino observatories (see next slide)



DM ID plot for European strategy briefing book

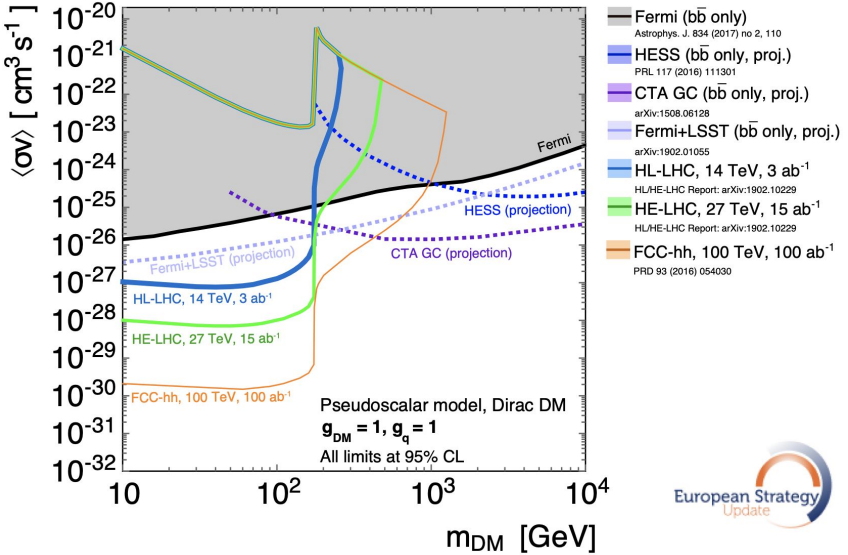
- Comparison of projected limits from future colliders with constraints from current and future indirect detection experiments (bottom right figure)
  - In the context of simplified s-channel pseudoscalar DM model
  - The collider limits are transferred via equations:
    - For quarks:

$$\langle \sigma v_{rel} \rangle_q = \frac{3 m_q^2}{2\pi v^2} \frac{g_q^2 g_{DM}^2 m_{DM}^2 \sqrt{1 - \frac{m_q^2}{m_{DM}^2}}}{(M_{med}^2 - 4 m_{DM}^2)^2 + M_{med}^2 \Gamma_{med}^2}$$

    - For gluons:

$$\langle \sigma v_{rel} \rangle_g = \frac{\alpha_s^2}{2\pi^3 v^2} \frac{g_q^2 g_{DM}^2 \mid \sum_q m_q^2 f(\frac{m_q^2}{m_\chi^2}) \mid^2}{(M_{med}^2 - 4 m_{DM}^2)^2 + M_{med}^2 \Gamma_{med}^2}$$

arxiv 1910.11775



European Strategy Update